The second SPACEINN local helioseismology working group meeting was held at Max-Planck-Institut für Sonnensystemforschung in Göttingen, Germany, on 4 September, 2014.

**Purpose of the SPACEINN local helioseismology working group meeting:**
One of the goals of SPACEINN WP4 project is to collect all available information about sources of systematic effects, some of which are known to a few instrument scientists or experts in data analysis, but not accessible to the broader community. This group meeting is for presentations and discussions for known systematics.

**Programme:**

SPACEINN local helioseismology working group meeting: Systematics

Chair: Kaori Nagashima(MPG)

<table>
<thead>
<tr>
<th>September 4, 2014</th>
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<tbody>
<tr>
<td>9:00 - 9:30</td>
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<tr>
<td><strong>Sylvain Korzennik</strong></td>
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<tr>
<td>(Harvard-Smithsonian Center for Astrophysics)</td>
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<tr>
<td>What can we learn about the solar subsurface large scale flows from accurate high-degree modes frequencies?</td>
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<tr>
<td>9:30 - 10:00</td>
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<tr>
<td><strong>Thomas L. Duvall Jr.</strong></td>
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<td>(MPG)</td>
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<td>A new time-distance measurement of meridional circulation that is not susceptible to center-to-limb effects</td>
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<tr>
<td>10:00 - 10:40</td>
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<td>Coffee break</td>
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<td>10:40 - 11:00</td>
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<tr>
<td><strong>Timothy Larson</strong></td>
</tr>
<tr>
<td>(Stanford University)</td>
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<tr>
<td>Medium-degree analysis of Mount Wilson data</td>
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<tr>
<td>11:00 – 11:20</td>
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<tr>
<td><strong>Kaori Nagashima</strong></td>
</tr>
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<tr>
<td>11:40 - 12:00</td>
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<tr>
<td><strong>Ariane Schad</strong></td>
</tr>
<tr>
<td>(KIS)</td>
</tr>
<tr>
<td>Distortion of global mode eigenfunctions</td>
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</table>
Some photos of the meeting

At the beginning, the chair is explaining the purpose of the meeting.

T. Duvall is giving a talk.

T. Larson is giving a talk.
Participants:

Antia, H.M. (Tata Institute of Fundamental Research)
Appourchaux, Thierry (UPS IAS)
Ayukov, Sergey (Moscow State University)
Baker, David M. (MPG)
Barekat, Atefeh (MPG)
Ball, Warrick (Georg-August-Universität Göttingen)
Baturin, Vladimir (Moscow State University)
Baudin, Frédéric (UPS IAS)
Bhattacharya, Jishnu (Tata Institute of Fundamental Research)
Birch, Aaron (MPG)
Bogart, Richard (Stanford University)
Böning, Vincent (KIS)
Brandenburg, Axel (NORDITA)
Braun, Douglas (NorthWest Research Associates)
Broomhall, Anne-Marie (University of Warwick)
Cally, Paul (Monash University)
Cameron, Robert (MPG)
Davies, Guy (University of Birmingham)
Duvall, Jr., Thomas L. (MPG)
Fleck, Bernhard (ESA)
Fournier, Damien (Georg-August-Universität Göttingen)
Gangadharan, Vigeesh (KIS)
Garcia, Rafael A. (CEA)
Gizon, Laurent (MPG)
Glogowski, Kolja (KIS)
Hanasoge, Shravan (Tata Institute of Fundamental Research)
Hill, Frank (AURA NSO)
Holzwarth, Volkmar (KIS)
Howe, Rachel (University of Birmingham)
Ilonidis, Stathis (Stanford University)
Kiefer, René (KIS)
Komm, Rudolf (AURA NSO)
Korznennik, Sylvain (Harvard-Smithsonian Center for Astrophysics)
Küker, Manfred (Leibniz Institute for Astrophysics Potsdam)
Langfellner, Jan (Georg-August-Universität Göttingen/MPG)
Larson, Timothy (Stanford University)
**Outcome of the meeting:**

Based on the talks of the meeting and the personal discussions between the participants of the meeting, we have set up a website where anyone can access information about sources of systematic effects of observation datasets related to helioseismology analysis. We will keep collecting the information and will update the information when needed. (The final version of this website will become a part of Deliverable D4.13 “Report on systematic effects”)

**The website about the systematics:**
http://www2.mps.mpg.de/projects/seismo/SpaceInn/systematics.html

Link to this webpage is available from the “Observations” button on SPACEINN WP4 Local Helioseismology top page.

**Screenshot of the website:**

![SpaceInn.eu](image-url)
## Appendix

### Presentations at the meeting

<table>
<thead>
<tr>
<th>1. Sylvain Korzennik (Harvard-Smithsonian Center for Astrophysics)</th>
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<td>Distortion of global mode eigenfunctions</td>
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<tr>
<td>7. Richard Bogart * (Stanford University)</td>
<td>HMI Local Helioseismology Data: Status and Prospects</td>
</tr>
</tbody>
</table>

* Richard Bogart was a participant of the meeting, and we discussed with him about the systematics. Here we attached his document about the systematics as well.
1. Sylvain Korzennik

What Can We Learn about the Solar Subsurface Large Scale Flows from Accurate High-Degree Modes Frequencies?

Helas VI — SOHO 28 — SPACEINN
Göttingen, GE

S.G. Korzennik
Harvard-Smithsonian Center for Astrophysics, USA.

September 2014

Contributors: A. Eff-Darwich (ULL, IAC)
T. Larson (Stanford)
M.C. Rabello-Soares (UFMG)
J. Schou (MPS)
S.G. Korzennik (CfA)

Introduction

High degrees “problem”:
- modes blend into ridges ($\ell > 200$, for p-modes, $\ell > 300$ for f-modes),
- ridge characteristics ($\nu$, $A$, $\Gamma$, $\alpha$) are not the mode characteristics.

Methodology
- Fit ridges ($100 \leq \ell \leq 1000$),
- Use multi-taper estimator (to reduce realization noise).
- Apply a ridge to mode correction, based on best possible model of mode blending - dominated by the effective leakage matrix.
- Iterate on model input parameters to best match observations.
- Use the $100 \leq \ell \leq 300$ overlap for validation.

Coverage in the ($\ell$, $\nu$) Plane

- Red dots: low and intermediate degrees: fitting resolved modes.
- Black circles: high degrees modes: ridge fitting.

Data Sets Analyzed

<table>
<thead>
<tr>
<th>Year</th>
<th>Instrument</th>
<th>2001 90 day long</th>
<th>2002 98 day long</th>
<th>2010 67 day long</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDI</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GONG</td>
<td>√</td>
<td>√</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HMI</td>
<td></td>
<td></td>
<td>√</td>
<td></td>
</tr>
</tbody>
</table>

- All epochs correspond to MDI Dynamics epochs.
- Can extend the time series for HMI & GONG.

Comparison with Resolved Modes

<table>
<thead>
<tr>
<th>Year</th>
<th>Instrument</th>
<th>$\Delta \nu$ [\mu Hz]</th>
<th>$\Delta \nu/\sigma_{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>MDI</td>
<td>$-0.220 \pm 0.673$</td>
<td>$-0.880 \pm 2.182$</td>
</tr>
<tr>
<td>2002</td>
<td>MDI</td>
<td>$-0.298 \pm 0.966$</td>
<td>$-0.862 \pm 2.631$</td>
</tr>
<tr>
<td></td>
<td>GONG</td>
<td>$0.176 \pm 0.769$</td>
<td>$0.517 \pm 2.416$</td>
</tr>
<tr>
<td>2010</td>
<td>MDI</td>
<td>$-0.088 \pm 1.087$</td>
<td>$-0.077 \pm 2.766$</td>
</tr>
<tr>
<td></td>
<td>GONG</td>
<td>$0.748 \pm 1.186$</td>
<td>$2.751 \pm 2.411$</td>
</tr>
<tr>
<td></td>
<td>HMI</td>
<td>$0.269 \pm 0.616$</td>
<td>$0.880 \pm 2.044$</td>
</tr>
</tbody>
</table>

- Mean and standard deviation of
  - frequency differences, and
  - frequency differences normalized by their uncertainties,
- between estimated mode frequencies derived from ridge fitting and coeval resolved mode frequencies measurements,
- for the $100 \leq \ell \leq 200/300$ overlapping range.

Comparison with Resolved Modes (cont’d)

Circles: frequency differences; dots: ridge to mode correction
- Differences are small, clustered near zero, with no discernible trends, and much smaller than the correction itself.
- The largest scatter is seen for the f-mode below $\ell = 250$ or so.
Comparison with Resolved Modes

- Similar plot for MDI, GONG and HMI 2010.
- GONG comparison shows a larger bias ($2.8\sigma$).
- Scatter for the f-mode remains large even above $\ell = 250$.
- Is this the result of using a shorter time series (67 versus 90 or 98 days).

Comparison at High Degree between Data Sets

<table>
<thead>
<tr>
<th>Year</th>
<th>Instruments</th>
<th>$\Delta \nu$ [\mu Hz]</th>
<th>$\Delta \nu/\sigma_{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>GONG – MDI</td>
<td>$-0.222 \pm 0.460$</td>
<td>$-1.317 \pm 1.470$</td>
</tr>
<tr>
<td>2010</td>
<td>GONG – MDI</td>
<td>$-0.982 \pm 0.934$</td>
<td>$-4.260 \pm 2.770$</td>
</tr>
<tr>
<td></td>
<td>HMI – MDI</td>
<td>$-0.655 \pm 1.117$</td>
<td>$-2.162 \pm 1.572$</td>
</tr>
</tbody>
</table>

- Mean and standard deviation of frequency differences, and frequency differences normalized by their uncertainties, between estimated mode frequencies derived from ridge fitting for different instruments and coeval epochs, with respect to MDI values.

Comparison of Clebsch–Gordan Coefficients

- Color dots: coefficients derived from ridge fitting.
- Black crosses: coefficients derived from coeval resolved mode fitting.
- Large offset between ridge and mode estimate, and between instruments.

By contrast with the 2002 data, the frequency comparison shows a variation with degree, and some dependence on frequency.

Color circles: coefficients derived from mode estimates, after correcting ridge fitting results.
Black crosses: coefficients derived from coeval resolved mode fitting.
Despite horns, both the offset high degree and mode estimate, and between instruments has vanished — no ad hoc fudging.
Rotation Inversions

- Inversion model grid (semi uniform in radius and latitude),
- shown in cartesian coordinates.


Averaging Kernels

- Kernels for inversions using or not high degree modes (left vs right)

- Target location: black cross-diamond symbols,
- Kernel center of gravity and width: green crosses and circles.
- Inversion grid: black dots.

Averaging Kernels (Cont'd)

- Top 10%

Rotation Rate in the Outer 10% of the Solar Interior

- after subtracting a differential rotation profile, inferred using or not high degree modes (right and left panels).

Note

- (a) the “torsional oscillations” signal stands out more clearly when including high degrees, and
- (b) the profiles are quite different in the top 5%, esp. at high latitudes.
Conclusions

- Can use ridge values to estimate mode parameter.
- Discrepancies remain, likely due to short time series, error in PSF, ...
- GONG, MDI & HMI overlap can be leveraged to resolve this.
- Inclusion of high degree splittings affects solution in the top 10%, and alters the solution in the top 5%.
- Should produce and use high-degree mode estimates on a regular basis.

Tables are available at
https://www.cfa.harvard.edu/~sylvain/research/
under
https://www.cfa.harvard.edu/~sylvain/research/tables/HiL/
Time-distance measurements of meridional circulation using pairs of points at equal center-to-limb angle

Tom Duvall
Deep Chakraborty
Tim Larsen

Examples of ray paths for measuring meridional circulation (left); expected travel-time differences for a single radial cell model (right)

The problem: east-west signal very similar to north-south

Geometry for measurement technique
Analysis steps:

- 1) Each HMI image is put onto a longitude-sin(latitude) coordinate system (Tim).
- 2) Spherical harmonics computed for l<=300 (Tim).
- 3) Images reconstructed on azimuth-heliocentric angle coordinate system for 1 year. This involves putting $b_0$ back in. (Tom, Deep, Tim, Shukur).
- 4) Filtering is done only as a 1st difference in time. (Tom).
- 5) Cross correlations for each day for different lags in azimuth and at the different heliocentric angles separately.
- 6) Average correlations over 1 year.
- 7) Travel times computed using the Gizon-Birch method. A separate reference cross correlation is computed for each heliocentric angle.
- 8) Travel time differences are computed for oppositely directed waves.
- 9) Symmetric and antisymmetric components about the central meridian to separate rotation and meridional circulation.

Summary

- Big question: is there sufficient s/n to make progress? Not sure.
- Big question: have we really gotten away from center-to-limb systematic errors? Don’t know yet.
3. Tim Larson

Medium-I Analysis of Mount Wilson Data

tim larson
tplarson@sun.stanford.edu
Stephen Pinkerton, Ed Rhodes
USC
Jesper Schou
MPS
**Types of Data**

- Filters: Na (mostly) or K (1997)
- Cameras
  - TALKTRONICS: 1024x1024, 2002 (testing)

**P-angle Drift**

- Ring diagram analysis reveals “washing machine” effect
- Auto-correlation with averaged images throughout the day indicates value of 0.018 degrees/hour
- Cross-correlations with MDI indicates value of 0.012 degrees/hour
Zonal flows from MWO/MDI f modes

1996 97 98 99 00 01 02 03 04 05 06 07 08 09 10 11

That's all Folks!
SDO/HMI multi-height velocity measurements

Kaori Nagashima (MPS)

Collaborators:
L. Gizon, A. Birch, B. Löptien, S. Danilovic, R. Cameron (MPS),
S. Couvidat (Stanford Univ.),
B. Fleck (ESA/NASA), R. Stein (Michigan State Univ.)

- We confirm that we can obtain velocity information from two layers separated by $\sim \frac{1}{2} H_p$ from SDO/HMI observations
- They are useful for, e.g., multi-layer helioseismology analyses & study of energy transport in the atmosphere, as well as understanding the center-to-limb variations of helioseismology observables?

1. **Standard HMI Dopplergram**

   (Couvidat et al. 2012)

   - HMI takes filtergrams at 6 wavelengths around Fe I absorption line at 6173 Å
   - Calculate the line shift based on the Fourier coefficients of the 6 filtergrams

   \[
   v = \frac{1}{T} \sum_{i=1}^{6} \frac{1}{a_i} \left( \frac{1}{a_i} \right) \sin \left( \frac{2\pi}{\lambda} \right)
   \]

   - + some additional calibration to make the standard Dopplergrams (i.e., pipeline products)

   Formation layer @ ~100km above the surface (Fleck et al. 2011)

   Similar to the formation layer of the center of gravity of the 6 filtergrams.

---

To extract multi-height info, at first, we made 3 simple Dopplergrams. But it did not work well.

- **Doppler signal:**

  \[
  V = f \left( \frac{I_b - I_c}{I_b + I_c} \right)
  \]

  - fitting the average Doppler signals by 3rd order polynomial using the SDO orbital motion

- **wavelength separation (and dynamic range) is limited**

---

We tried several other definitions of Dopplergrams, and found these two look good.

1. **Average wing** (for deeper layer)

   - Calculate the Doppler signals using the average of each blue and red wing.
   
   \[
   I_b - I_c \quad (I_b = \frac{I_b + I_r}{2}, \quad I_c = \frac{I_b + I_r}{2})
   \]

   Convert the signal into the velocity:
   1. Calculate the average line profile
   2. Parallel-Dopplershift the average line profile
   3. Calculate the Doppler signals
   4. Fit to a polynomial function of the signal

---

2. **Line center** (for shallower layer)

   - Doppler velocity of the line center derived from 3 points around the minimum intensity wavelength
   - Calculate the parabola through the 3 points and use its apex as the line shift

   So, we have
   1. Average-wing Dopplergrams
   2. Line-center Dopplergrams
   3. And Standard HMI Dopplergrams (pipeline products)

   Now we have 3 Dopplergrams!

Are they really “multi-height” Dopplergrams? (1)

→ Estimate of the “formation height” using simulation datasets (STAGGER/MURaM)
Are they really “multi-height” Dopplergrams? (1)

⇒ Estimate of the “formation height” using simulation datasets

1. Use the realistic convection simulation datasets: STAGGER (e.g., Stein 2012) and MURaM (Vögler et al. 2005)
2. Synthesize the Fe I 5273 Å absorption line profile using SPINOR code (Frutiger et al. 2000)
3. Synthesize the HMI filtergrams using the line profiles, HMI filter profiles, and HMI PSF
4. Calculate three Dopplergrams:
   - Line center & Average wing & standard HMI
5. Calculate correlation coefficients between the synthetic Doppler velocities and the velocity in the simulation box

Sample synthetic Dopplergrams (10Mm square)

Estimate of the “formation height” using simulation datasets
Correlation coefficients between the synthetic Doppler velocities and the velocity in the simulation box

<table>
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<tr>
<th>Peak heights</th>
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<tbody>
<tr>
<td>Line center 221 km</td>
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<tr>
<td>Standard HMI 155 km</td>
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<tr>
<td>Average wing 170 km</td>
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Estimate of the “formation height” using simulation datasets
Correlation coefficients between the synthetic Doppler velocities and the velocity in the simulation box

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<tr>
<td>Line center 144 km</td>
</tr>
<tr>
<td>Standard HMI 118 km</td>
</tr>
<tr>
<td>Average wing 92 km</td>
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Correlation coefficients between the synthetic Doppler velocities and the velocity in the simulation box

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<tr>
<th>Peak heights</th>
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<tbody>
<tr>
<td>Line center 150 km</td>
</tr>
<tr>
<td>Standard HMI 110 km</td>
</tr>
<tr>
<td>Average wing 80 km</td>
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</tbody>
</table>

The correlation coefficients has a wide peak

⇒ Vz itself has a wide correlation peak

Vz auto-correlation coefficient in the wavefield

The width of the correlation peak is so large.

Therefore, the Dopplergram of this wavefield should have such a wide range of contribution heights.
Contribution layer is higher when the resolution is low (i.e., w/ PSF)
• If the formation height in the cell is higher
  – In the cell it is brighter than on the intergranular lane
  – The cell contribution is larger than the intergranular lane’s contribution?
  – Therefore, the contribution layer is higher?

Are they really “multi-height” Dopplergrams? (2)
→ Phase difference measurements

Check the height difference with Response function

We calculate Response function using STD PRO in SPINOR code (Frutiger et al. 2000)
Definition:
\[ I(\lambda_2) - I(\lambda_1) \]
\[ = \int_{\Omega} \left( V(r) - V'(r) \right) dr \]
\[ V\prime(r) \text{ vertical velocity field at optical depth } \tau \]

Phase difference between Doppler velocity datasets from two different height origins
- Significant phase difference is seen. Surely they are from different height origin.
- Rough estimate:
  1. Photospheric sound speed: \( c_p \approx 7\) km/s
  2. Phase difference measured: \( \Delta \phi = -30(\text{deg}) \) at 8mHz

\[ \Delta z \approx 73\text{km} \]
This means...what?

Phase difference (CO\textsuperscript{5}BOLD case)
Fig. 1 in Straus et al. 2008

Upper boundary of the atmosphere:
STAGGER 550km, CO\textsuperscript{5}BOLD 900km

They have
- negative phase shift above the acoustic cutoff,
  same as STAGGER’s results
- positive phase shift in the lower frequency ranges (atmospheric gravity waves)
  different from STAGGER’s results

IBIS obs. CO\textsuperscript{5}BOLD
Phase difference of the velocity fields at 250km and 70km above surface

– No significant phase difference (in p-mode regime)
– Atmospheric gravity wave? (e.g., Straus et al. 2008, 2009)
– \( \Delta z \approx 73\text{km} \)

Phase difference of the high resolution data

IBIS obs. CO\textsuperscript{5}BOLD
Solid: HMI obs.
Dotted: STAGGER
• Line-center
• HMI-algorithm
• Average-wing

In the STAGGER power map there are some power enhance in the convection regime.

So... summary of the phase difference

• P-mode regime: phase difference is small because they are eigenmons.
• $\omega > \omega_{\text{cut}}$: upward-propagating wave
  – phase difference found in observation data and STAGGER data have similar trends.
  – $\omega_{\text{cut}}$ in STAGGER atmosphere is lower than that of the Sun.
• Convective regime (lower frequency, larger wavenumber)
  – Observation: positive phase difference indicates the atmospheric gravity waves
  – STAGGER: no such feature
    • Atmospheric extent (about 550 km) of STAGGER data might not be sufficient for the atmospheric gravity waves.
    • Radiative damping of the short-wavelength waves in the STAGGER is stronger than the Sun?
    • or...?

Summary

• We propose two Dopplergrams other than the standard HMI-algorithm Dopplergram:
  – line-center Dopplergram (30-40 km above the standard)
  – Average-wing Dopplergram (30-40 km below the standard)

• These are useful for understanding the center-to-limb variation of helioseismology observables (e.g., Zhao et al. 2012)?

The formation layer heights is higher in the region nearer the limb.

Calculation was done by SPINOR code.
Motivation: We need spherical Kernels.

- They are already used in the current scientific debate, e.g.:
  - Meridional flow measurements: e.g. Zhao et al. (2013), Kholikov et al. (2014).
  - Studies on supergranules: e.g. Duvall & Hanasoge (2013), Duvall et al. (2014).
  - Both perform modelling with ray approximation kernels.
- Born kernels not yet available in spherical geometry.
- Cartesian Born kernels used in HMI pipeline for subsurface flow inversions (e.g. Zhao et al., 2012).

How to calculate Born Kernels?

  - Solve zero and first order damped and stochastically driven wave equation.
  - Via Green’s functions, using Model S eigenfunctions.
  - Find expression for perturbed cross-correlation.
  - Find travel-time difference shift as a function of flow:
    $$\delta \tau_{\text{diff}} = \int K \cdot v \, d^3r.$$  
- And how to do spherical?

Sanity Check: The Cartesian Limit

- First attempts by Roth, Gizon & Birch (2006).
- Expand Green’s functions in spherical harmonics.
- Find a formula that can actually be calculated numerically.
- Validate the method.
Sanity Check: The Cartesian Limit

- With A. C. Birch & L. Gizon.
- Setup: point-to-point travel-times on equator, $\Delta = 10 \, \text{Mm}$
- $K_\phi(r, \theta, \phi) = K_x(x, y, z)$, sensitivity for zonal flows, horizontal cuts.
- Line asymmetry not taken into account: Both results only using $f$-mode ridge in computation.

Horizontal integrals: $K_\phi = K_x$, sensitivity for zonal flows.

From Cartesian BG2007 code (solid) and from spherical code (dashed).

Maximum value: 3 % off. Similar to additional consistency tests.

Validation of Method with Simulated Data

- Data and flow model (right) from Hartlep et al. (2013).
- Original flow model from Rempel (2006), amplified by factor of 36: $v_{\text{max}} = 500 \, \text{m/s}$ at the surface.
  - Do simulated and forward-modelled travel-times agree?
- Analysis done without filters, proceeding similarly to Hartlep et al. (2013).

Deep Meridional Flow Kernels: First results

- We compare kernels with different filters (no filter, low-pass in $l$, phase-speed).
- $K_\theta$, i.e. sensitivity to southward flow,
- cuts at central meridian and just below photosphere,
- $\Delta = 42.19 \, \text{deg}$ in N-S-direction,
- centered at latitude 40 degrees north,
- computation uses $l \leq 170$, same as simulation in Hartlep et al. (2013),
- modelling radial component of wavefield.
Unfiltered, $\Delta = 42.19$ deg

Distance in longitude [Mm]

Distance in latitude [Mm]

$\Delta = 42.19$ deg, filtered: $F(l, \omega) = \exp\left(-\frac{\rho}{2\delta l}\right)$, $\delta l = 50$

Distance in longitude [Mm]

Distance in latitude [Mm]

$\Delta = 42.19$ deg, filtered: $F(l, \omega) = \exp\left(-\frac{\rho}{2\delta l}\right)$, $\delta l = 20$

Phase-speed filt., $v_0 = 284.3 \text{ km/s}$, $\delta v = 7 \text{ km/s}$ (Kholikov et al., 2014)

Phase-speed filt., $v_0 = 284.3 \text{ km/s}$, $\delta v = 7 \text{ km/s}$, $\Delta = 42.19$ deg
How big is the sensitivity to the return flow? (Δ = 42 deg)

- Kernel integrated over Hartlep et al. (2013) meridional flow profile.

<table>
<thead>
<tr>
<th>Kernel</th>
<th>δτ for r/R⊙ ≤ 0.79</th>
<th>% of total δτ</th>
<th>ray kernels *</th>
</tr>
</thead>
<tbody>
<tr>
<td>unfiltered</td>
<td>-0.446 s</td>
<td>10.4 %</td>
<td>≈ 20 %</td>
</tr>
<tr>
<td>δl = 50</td>
<td>-0.489 s</td>
<td>13.4 %</td>
<td></td>
</tr>
<tr>
<td>δl = 20</td>
<td>-0.467 s</td>
<td>14.8 %</td>
<td></td>
</tr>
<tr>
<td>phase-sp.</td>
<td>-0.503 s</td>
<td>11.4 %</td>
<td></td>
</tr>
</tbody>
</table>

Table: Ray kernel value from Hartlep et al. (2013).

- Divide δτ by ≈ 25 to get realistic numbers: δτ,0.79 ≈ 0.02 s!
- The sensitivity is always concentrated in the upper convection zone.
- Ray and Born kernel values are quite different. Is that a problem?

⇒ Unfiltered kernel has smallest sensitivity to return flow.
⇒ Low-pass filtering in l gives the strongest relative sensitivity to return flow.
⇒ Phase-speed filtered kernels are best localised at the target depth.

Summary

1. We can adequately calculate spherical Born kernels:
   - Results from Cartesian geometry (BG2007) reproduced.
   - Effect of meridional flow correctly modelled (Hartlep et al., 2013).
2. Example kernels for meridional flow measurements:
   - 10-15% of the total sensitivity is due to the return flow for a standard meridional flow profile.
   - Ray and Born kernels have different sensitivity to return flow by a factor of 2.
   - Low-pass filtering in l gives the strongest relative sensitivity to return flow.
   - Phase-speed filtered kernels are best localised at target depth.

Thank you very much!
References

- Zhao et al. (2013)
- Kholikov et al. (2014)
- Duvall & Hanasoge (2013)
- Duvall et al. (2014)
- Zhao et al. (2012)
- Gizon and Birch (2002)
- Birch and Gizon (2007, BG2007)
- Roth, Gizon & Birch (2006)
- Hartlep et al. (2013)
- Rempel (2006)
- Gizon and Birch (2004)
Low-pass $\ell$, $\delta \ell = 20$

Phase-speed

Unfiltered Kernel

Low-pass $\ell$, $\delta \ell = 50$
$v_{\text{max}} = 500 \text{ m/s still in linear regime?}$

For $\Delta = 22.5 \text{ deg}$, travel-times from E-W-kernel (dashed) at equator and exact perturbed cross-correlation (crosses, method see Jackiewicz et al., 2007) for a solid body rotation corresponding to a certain equatorial zonal flow speed ($x$-axis): Linear regime extends to these flow speeds.

Sanity Check: The Cartesian Limit

$K_\phi = K_x$, sensitivity for zonal flows, integrated wrt depth, cut along $y = 0$:

$K_\theta = -K_y$, sensitivity for meridional flows.

$K_r = K_z$, sensitivity for convective flows.
6. Ariane Schad

**Distortion of global mode eigenfunctions - Measuring meridional flow and solar rotation**

Ariane Schad\(^{1,2}\), Jens Timmer\(^2\), Markus Roth\(^1\)

\(^{1}\)Kiepenheuer-Institut für Sonnenphysik
\(^{2}\)Freiburg Center for Data Analysis and Modeling, University of Freiburg

HELAS VI / SOHO-28 / SpaceInn
04 September 2014
Göttingen, Germany

> flows lead to a coupling of modes in a "neighborhood" \(K_{k}\) of a mode \(k=(n,l,m)\):

\[
\phi_{k}(r,\theta,\phi) = \sum_{k' \in K_{k}} c_{k'k} \phi_{k'}(r,\theta,\phi).
\]

(Perturbed eigenfunction)

\[
\phi_{k}(r,\theta,\phi) = \sum_{k' \in K_{k}} c_{k'k} \phi_{k'}(r,\theta,\phi).
\]

(Unperturbed eigenfunction)

> \(c_{kk'}\) – coupling coefficient between mode \(k, k'\) (coupling strength):

\[
c_{kk'} = -\frac{1}{2\pi} \int \rho_{k'} \cdot \left( \frac{1}{r} \nabla \phi_{k} \right) \, d\Omega,
\]

(1. order approximation)

Spherical harmonic representation of \(u\):

\[
u(r) = \sum_{s,s=\pm 1,2,3,4} \sum_{l} \sum_{m=-l}^{l} u_{l,m}^{s}(r) Y_{l,m}^{s}(\theta,\phi)
\]

(conservation of mass)

Polynomial expansion of coupling coefficients:

\[
c_{kk'} = c_{kk'}(m) \approx \sum_{s} c_{s}^{kk'}(r) P_{s}^{m}(r)
\]

(b-coefficients)

> knowing \(\{c_{s}^{kk'}\}\) one can infer the flow coefficients \(u_{l,m}^{s}\) & \(v_{l,m}^{s}\)!

**Effect of mode coupling on global oscillation data**

SHT of full-disk Dopplergrams:

\[
\phi_{l,m}^{s}(\omega) = \int Y_{l,m}^{s} W(\theta,\phi) \, d\Omega - \sum_{k \in K_{n}} c_{kk'} \phi_{k}(\omega) \frac{d^{2}Y_{l,m}^{s}}{d\theta^{2}}(\theta,\phi)
\]

\(t_{bb}\) – leakage matrix elements (imperfect orthogonality: line of sight projection, solar disk, etc.)

Measure for cross-talk in SHT data: (Fourier) amplitude ratio: between reference mode \(k=(n,l,m)\) and coupling modes \(k'\)

\[
\frac{\phi_{k}(\omega_{0})}{\phi_{k}(\omega_{0})} = \sum_{k' \in K_{k}} c_{kk'} \phi_{k}(\omega) \frac{d^{2}Y_{l,m}^{s}}{d\theta^{2}}(\theta,\phi)
\]

(Schad et al., ApJL 2013)

**Evaluation of the method**

How can we evaluate the method and the reliability of the result?

> analysis of simulated acoustic wave fields
> comparison of flow measurements from different methods: here for rotation!

**Application to MDI data - superimposed flow components (s =2,4,6,8)**

> MDI data 2004-2010, \(s=1,...,8\)

> complex flow pattern in latitude & depth
> in contrast to "prevalent" picture of two flow cells


(Schad et al., ApJL 2013)
Evaluation: Analysis of simulated acoustic wavefield

- 3D simulation of acoustic wavefield (T. Hartlep et al. 2013)
  - meridional flow (500 m/s)
  - \( T = 2.7d \)
  - \( dt = 30t \)
  - \( l = 1,...,170 \)
  - without leakage

Evaluation: Analysis of simulated acoustic wavefield - results

- 3D simulation of acoustic wavefield (T. Hartlep et al. 2013)
  - meridional flow (500 m/s)
  - \( T = 2.7d \)
  - \( dt = 30t \)
  - \( l = 1,...,170 \)
  - without leakage

Inversion for rotation – first results

- Rotation rate profile from splitting - coefficients (J. Schou)
  - MDI data (2004-2010)
  - 1 ≤ \( s \) ≤ 200
  - superimpose components with \( s = 1 \) : cross-coupling, i.e., a-coefficients not sensitive to \( s = 1 \) (i.e., "mean" rotation rate)
Inversion for rotation – first results

\[ \Omega(\tau, \theta, \phi) = \sum_{\ell=1}^{9} w_\ell(\tau) Y_\ell^m(\theta, \phi) \]

- splitting coeff.: \( w_3-w_9 \)
eigenfunctions: \( w_3-w_9 \)

> similar rotation profiles, but significant differences
> larger errors from eigenfunction perturbation analysis

Summary

> analysis of simulated data – resembles flow, differences must be cleared
> rotation profiles are similar, but there are significant differences
> origin so far unclear: - leakage matrix
  - numerical: SOLA inversion
  - parameter estimation – nonlinear model > bias?
  - theoretical eigenfunctions of p modes - how good are they, esp. near the surface?

> disentangle numerical from solar issues
> test different leakage matrices
> compare different inversion methods (SOLA, RLS,...)
> analyze further data (simulated, HMI)

Thank you for your attention!

Thanks to
Markus Roth, Kiepenheuer Institut für Sonnenphysik, Freiburg
Jens Timmer, University of Freiburg, Freiburg Center for Data analysis and modeling
MDI data & leakage matrix
Jesper Schou, MDI & HMI team, MPS Göttingen
Tim Larson, MDI & HMI team, Stanford University

Inversion for rotation: comparison of results

> Results for s=2,...,9:
  - splitting coeff. (black)
  - eigenfun. perturbation (blue)
Results for $s=2,...,9$:
- splitting coeff. (black)
- eigenfun. perturbation (blue)
### 7. Richard Bogart

**HMI Local Helioseismology Data: Status and Prospects**

Richard Bogart

Stanford University

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#### Local Helioseismology Data Products

<table>
<thead>
<tr>
<th>series</th>
<th>module</th>
<th>cadence (sec/rec)</th>
<th>size (MB/rec)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>hmi.V_avg120</td>
<td>datavg</td>
<td>396000</td>
<td>60</td>
<td>1/3 rotation averages of Dopplergrams with orbital velocity removed, for detrending</td>
</tr>
<tr>
<td>hmi.rdVtrack_fd05</td>
<td>mtrack</td>
<td>12</td>
<td>18</td>
<td>mosaics of the power spectra of the tracked tiles of the same hmi.rdVtrack_fd05, with Postel's mapping of most parameters</td>
</tr>
<tr>
<td>hmi.V_45s</td>
<td>mtrack</td>
<td>340</td>
<td>472</td>
<td>15° power spectrum of the tracked tiles in the series hmi.rdVtrack_fd*, with 1-to-1 mapping of most parameters</td>
</tr>
<tr>
<td>hmi.rdVpspec_fd05</td>
<td>pspec3</td>
<td>12</td>
<td>12</td>
<td>mosaics of the power spectra of the tracked tiles in the series hmi.rdVpspec_fd*, with 1-to-1 mapping of most parameters</td>
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<tr>
<td>hmi.rdVpspec_fd15</td>
<td>pspec3</td>
<td>340</td>
<td>324</td>
<td>15° power spectrum of the tracked tiles in the series hmi.rdVpspec_fd*, with 1-to-1 mapping of most parameters</td>
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<td>hmi.rdVpspec_fd30</td>
<td>pspec3</td>
<td>2500</td>
<td>648</td>
<td>15° power spectrum of the tracked tiles in the series hmi.rdVpspec_fd*, with 1-to-1 mapping of most parameters</td>
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<td>324</td>
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<tr>
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<td>datavg</td>
<td>34400</td>
<td>648</td>
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<td>hmi.rdVfits_fd05</td>
<td>ringfit</td>
<td>12</td>
<td>0.02</td>
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<tr>
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<td>hmi.rdVfitst_fd05</td>
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<td>12</td>
<td>0.1</td>
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<td>hmi.rdVfitst_fd15</td>
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<td>0.7</td>
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<td>hmi.rdVfitst_fd30</td>
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<td>0.9</td>
<td>mosaics of the “slow” (“structure”) fits to the power spectra in series hmi.rdVpspec_fd*</td>
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<tr>
<td>hmi.rdVfits_fd15_frame</td>
<td>rdvinv</td>
<td>98000</td>
<td>2.25</td>
<td>Flow inversions of the fits in all records for a given analysis time in series hmi.rdVfits_fd*</td>
</tr>
<tr>
<td>hmi.rdVfits_fd30_frame</td>
<td>rdvinv</td>
<td>196000</td>
<td>0.57</td>
<td>Flow inversions of the fits in all records for a given analysis time in series hmi.rdVfits_fd*</td>
</tr>
<tr>
<td>hmi.tdVinvrt_synopHC</td>
<td>invert_td_hr</td>
<td>993</td>
<td>22</td>
<td>Flow and sound-speed inversions of the travel time fits in series hmi.tdVtimes_synopHC</td>
</tr>
</tbody>
</table>

---

#### Tracked Doppler data - common input for most local helioseismology analysis

- Ring-diagram tiles at three size scales: 32°, 16°, and 5°. 12 “squares” (Uniform apodization to: 30°, 15°, and 5° circles)
- Time-distance tiles: 30°.72 “squares”
- R-D tile spacing: ~15°, 7.5°, and 2.5° in arc; T-D tile spacing: 24° in latitude and longitude
- R-D Longitude spacing depends on latitude, same as latitude spacing at equator, and subject to constraint of integer divisor of 360°
- R-D regions tracked while within 80° of disc center
- Three different sets, depending on heliographic latitude of SDO
- R-D regions tracked at Carrington rate
- Maximum photospheric zonal velocity 260 m/s at 50°
- Maximum photospheric drift rate 4°.34 / day at poles
- T-D regions tracked at nominal photospheric Doppler rate at center of region

---

#### Distribution of Ring-diagram Target Regions

- 15°
- 5°

---

#### Tracked Doppler data cubes, centred at 2152:210 (2014.07.09 08:45)

- 5° @ 12.5W07.5S
- 30° @ 15.0W00.0N

---

#### 15° power spectrum, 2151:240 (2014.06.09 21:36), 00.0W00.0N

- 2.5 mHz
- 3.5 mHz
- 5.0 mHz
**Ring-diagram Data Products**

Delay between Observation and Completion of Processing

**Time-distance Data Products**

Delay between Observation and Completion of Processing

**Prospects**

More of Same

Identical analysis (almost) applied to MDI, GONG, and Mt Wilson data sets

Ring-Diagrams

Addition of multi-ridge fit code to pipeline

Full-disc fit fits for 15° tiles

Improved fitting procedures to account for spatial variations

**Time-Distance**

...
HMI & MDI Coverage during Comparison Interval
2096:240 – 2098:015 (2010 05.01–07.12)

Differences in 4-year means of $r_d$f$i$ and $r_d$f$t$c flow parameters

$U_x$, $U_y$ (2.5 m/s contours)

Differences in 2.5-month means of $r_d$f$i$tm and $r_d$f$t$c flow parameters
(MDI data, 2096:150–2098:030)

$U_x$, $U_y$ (5 m/s contours)